PILE LOAD TESTS IN THE INCHEON BRIDGE PROJECT

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ABSTRACT: *For foundation of the Incheon Bridge, drilled shafts were applied as being supported by bearing capacity of rock sockets. 8 full-scale pilot piles were tested in both offshore site and onshore area prior to the commencement of constructions. Bi-directional loading method was used to verify the bearing capacity of the ground for both offshore site and onshore site. 3 of 4 piles of onshore site were tested using multi-level bi-directional method. World's largest compressive load beyond 30,000 tonf was applied per a pile. The construction process of instrumented pilot piles for preliminary pile load tests and performance of load testing are introduced. Results of the test are also reviewed.*

1. INTRODUCTION

Incheon Bridge Project is the construction of marine expressway bridge with total length of 18.4 km, linking Songdo New Town to the northern east side of connecting road of Incheon International Airport over the navigational channel of Incheon Port. For foundation piles, drilled shafts were applied as being supported by bearing capacity of weathered rock, soft rock or hard rock. The pile diameter is up to 3.0 m. The foundations of the private-financed section were designed using LRFD (Load & Resistance Factor Design) method for the first time in Korea, whereas the government-financed section used the conventional ASD (Allowable Stress Design) method. Moreover, contractors for each section of the government-financed section adopted different method for the design bearing capacity of drilled shafts. In order to verify the design of foundations pile load test was proposed before commencement of the government-financed section.

For the private-invested section of the project, in accordance with the CSR(Concessionaire Supplementary Requirements), 4 numbers of full-scaled piles were applied to the preliminary pile load test and their results were included in the design. Full-scaled load testing was carried out with Osterberg Cell loading method. Maximum load of 28,958 ton was loaded on 3 piles with 2.4m diameter and 1 pile with 3.0m diameter. This paper is to introduce construction process of

full-scaled load testing pile and performance of full-scaled load testing on the marine site which were successfully carried out. For the verification of bearing capacity of drilled shafts at Government-Financed sections of Incheon Bridge, 4 pile load tests(1 by single level bi-directional test and 3 by multi-level bi-directional test) were carried out prior to the commencement of constructions under joint controls of all contractors.

2. Geotechnical Site Characterization and Testing Plan

2.1 Offshore Area (Private-Investment Section)

In order to understand the quantitative condition of bed rock effecting the calculation of the bearing capacity on design and the actual bearing capacity of load testing pile, several tests such as Field Loading Test(LLT, PMT, GMJ, etc.) and Indoor Rock Testing(unconfined compression test, point load test, etc.) were carried out at the center of respective pile as well as soil investigation. Following Figure.1 is shows the results of soil investigation.

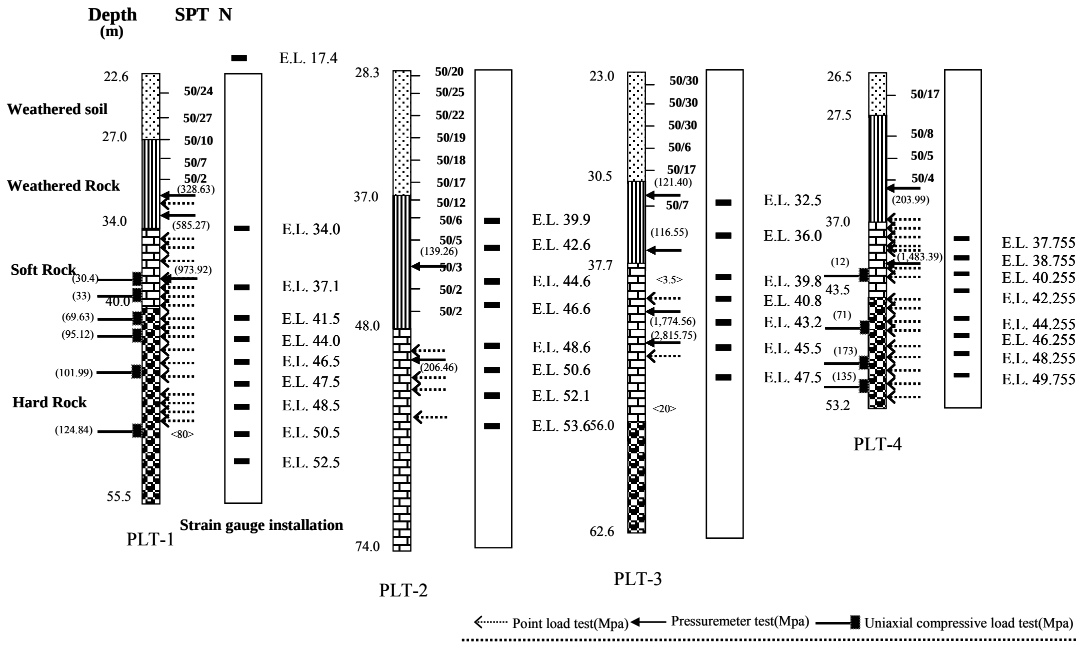


Figure 1 : Results of Soil Investigation for Preliminary Test

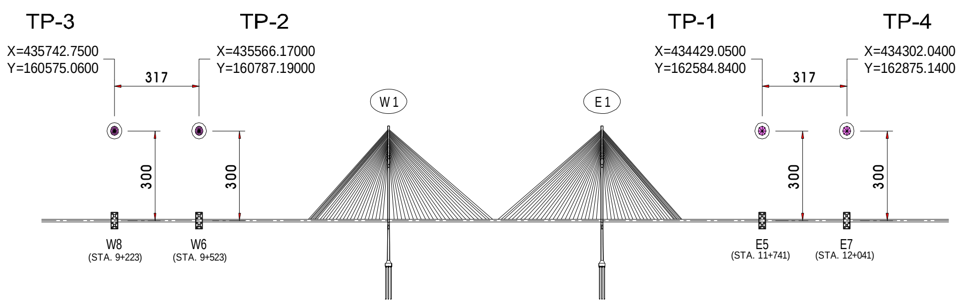


Figure 2 : Location of Load Testing Pile

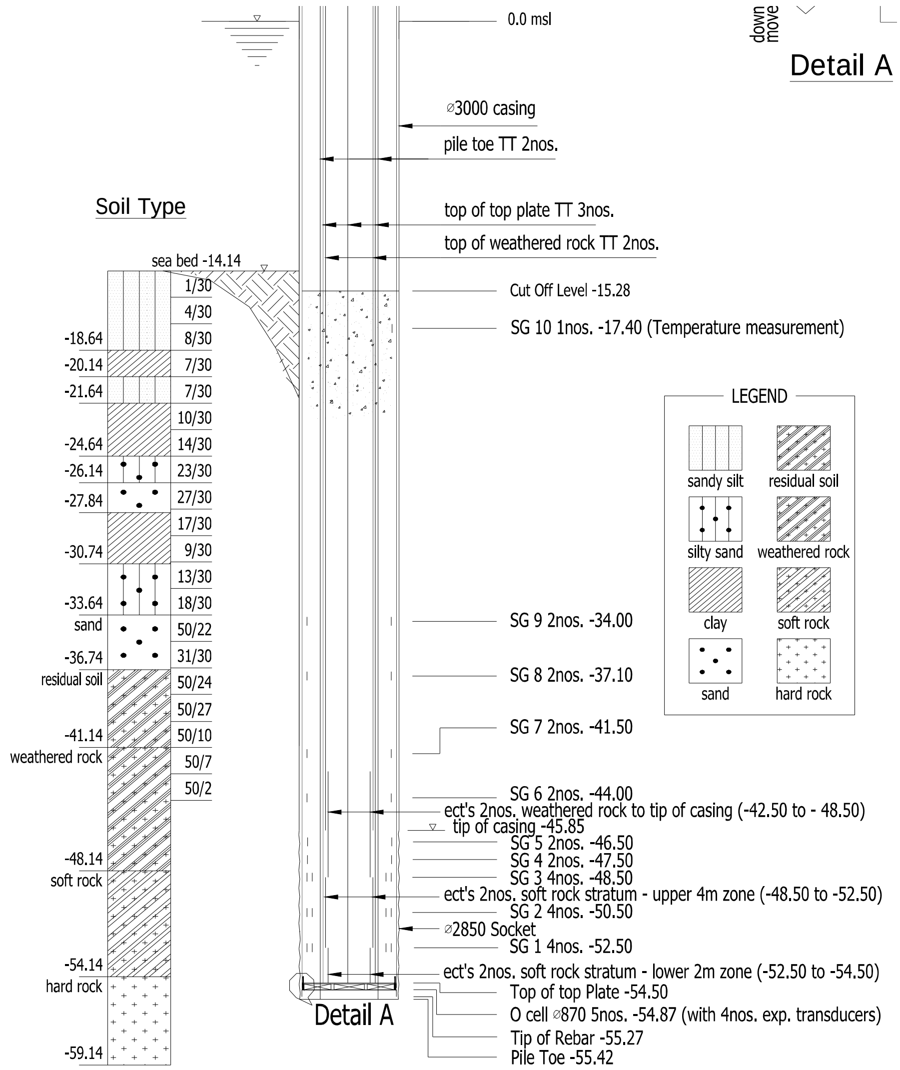
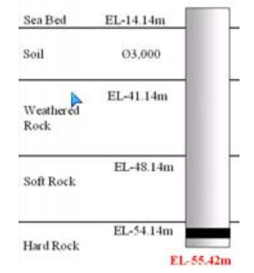
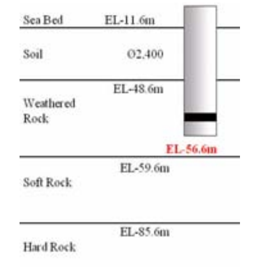
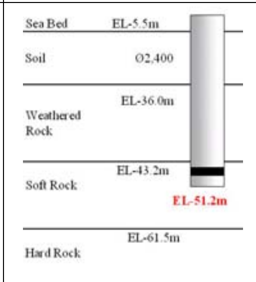
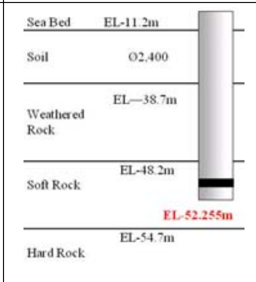


Figure 3 : Schematic of Instruments TP-1(E5)

Load testing is planned to be performed on the sea so as to have same condition of bridge construction. The testing was carried out at the location 300m north away from the navigational route in Viaduct since we failed to obtain the right of occupation of main navigational route in CSB section. The location of test piles is as shown in Figure.2. The concept of testing, purpose, pile toe condition, estimated bearing capacity and testing method are summarized in Table 1.
Loading plan for test pile was established after thorough surveying process in the view of settlement and bearing capacity, so as to have same loading and settlement at the both sides (bottom/top) of O-cell. Approximately 1.4 ~ 3.8 times of the estimated load was loaded on test pile to confirm ultimate level. As a measuring instrument to measure the load transfer, Vibrating Wire Type Strain Gauges were installed at intervals of 1.0 ~ 2.0m in consideration of thickness of soil layer in order to measure shaft friction of socket at supporting layer of weathered rock, soft rock and hard rock. And also, in addition to Telltale to measure the displacement of each part of testing pile, Embedded Compression Telltales (ECT-integrated of strain gauge and measuring rod) were installed to separately measure the displacement of weathered rock and soft rock. Expansion Transducers were installed between the bearing plates (bottom/top side) to measure the expansion of O-cell during load period. Figure.3 is showing the location of instruments on testing pile.

Table 1 : Loading Plan for Testing Pile & Pile Condition

	TP-1(E5) / (Φ 3,000mm)	TP-2(W6) / (Φ 2,400mm)	TP-3(W8) / (Φ 2,400mm)	TP-4(E7) / (Φ 2,400mm)
Concept				
Purpose	Confirms End Bearing of Hard Rock Confirms Skin friction of Weathered Rock Confirms Skin friction of Soft Rock	Confirms End Bearing of Weathered Rock Confirms Skin friction of Weathered Rock	Confirms End Bearing of Soft Rock Confirms Skin friction of Weathered Rock Confirms Skin friction of Soft Rock	Confirms End Bearing of Soft Rock Confirms Skin friction of Weathered Rock Confirms Skin friction of Soft Rock
Pile Toe Condition	Pile Toe Condition : Penetrates 0.92 m into Hard Rock (Cell top Plate on the top of hard rock)	Pile Toe Condition : Penetrates 8 m into Weathered Rock (Cell top Plate on the 1m from pile toe)	Pile Toe Condition : Penetrates 8 m into Soft Rock (Cell top Plate on the 1m from pile toe)	Pile Toe Condition : Penetrates 4.055 m into Soft Rock (Cell top Plate on the 1m from pile toe)
Estimated Bearing Capacity	Ultimate Bearing Capacity : 24,160 tonf Skin Friction : 7,520 tonf End Bearing : 16,640 tonf	Ultimate Bearing Capacity : 3,500 tonf Skin Friction : 2,400 tonf End Bearing : 1,100 tonf	Ultimate Bearing Capacity : 15,590 tonf Skin Friction : 7,550 tonf End Bearing : 8,040 tonf	Ultimate Bearing Capacity : 9,730 tonf Skin Friction : 5,160 tonf End Bearing : 4,570 tonf
Test Method and O-Cell Place	Single-Level Test Pile Toe (Hard Rock)	Single-Level Test Pile Toe (Weathered Rock)	Single-Level Test Pile Toe (Soft Rock)	Single-Level Test Pile Toe (Soft Rock)
Effective Pile Length	40.143m	44.2m	45.1m	40.01m
Other Attachment	Gauge, Sonic Tube	Strain Gauge, Sonic Tube	Strain Gauge, Sonic Tube	Strain Gauge, Sonic Tube
Target Load	21,000 ton	9,000 ton	17,000 ton	12,000 ton
Load Achieved	28,958 ton	13,799 ton	24,531 ton	17,369 ton
Test Pile Property	- O-cell Quantity : 5 EA - Concrete level : Seabed (–)90cm	- O-cell Quantity : 2 EA - Concrete level : Seabed (–)90cm	- O-cell Quantity : 4 EA - Concrete level : Seabed (–)90cm	- O-cell Quantity : 3 EA - Concrete level: Seabed (–)90cm

2.2 Onshore Area (Government-Financed Section)

In order to select the location of each test pile, total 8 bore holes were drilled to choose 4 of them. The location was selected to incorporate the test objective and every section as much as possible. The bedrocks are granite and granitic gneiss. 2 boring machines were employed for the investigation, and the SPT energy ratio of each was 43% (doughnut hammer) and 52% (safety hammer). The criterion of weathered rock was 50 blows per 15 cm penetration and N60 was used. For retrieving cores in weathered rock layers, triple core barrels were used, and total 28 unconfined compression tests were done for rock cores of the test location and point load test was done for 7 ~ 16 cores per borehole. Pressuremeter tests were also applied.

Table 2 : Classification and Rock Core Strength at Tip of Piles

	Section 2	Section 3	Section 4	Section 5
Weathered Rock	–	N.A. ($N \geq 50/15$)	–	–
Soft Rock	100 ~ 200	250 ~ 450	100 ~ 200	≥ 700
Hard Rock	–	250 ~ 900	–	≥ 1000

[unit of strength : kgf/cm^2]

Each site section was different in the soil and rock classification as well as the pile design method. The criteria for weathered rock classification were 50 blows/10 cm penetration or 50/15. Soft and hard rock classification criteria adopted for each section were also different(Table 2).
Skin friction and end bearing capacity was estimated based on empirical relations proposed many researches. The capacity by each method was compared and selected to conservative re-

sult. For weathered rock layer, skin friction of 20 tonf/m2 was assigned or evaluated using IGM analysis(FHWA, 1999).

Bi-directional pile load test is carried out by embedding water or oil pressured loading unit. This loading unit is composed of one or more loading jacks and plates above and below them. The load in the loading unit is applied upward and downward at the same time and this doubles the test load, and the resistance in one direction acts as a reaction of the other direction eliminating the need for the huge massive reaction structure in conventional static load test. However, the loading capacity is limited by the number and capacity of jacks which can be assembled in one layer of loading unit, and one layer of loading unit is not enough to find the ultimate capacity, sometimes. In this case, two or more layers of loadings can be installed in one pile dividing the test sections in order to save time and cost for the load test of multiple piles. In multi-level bi-directional test, loading sequences of each loading units can be selected considering the test condition and the result of the previous stages. Figure 4 represents the loading sequence applied in this project.

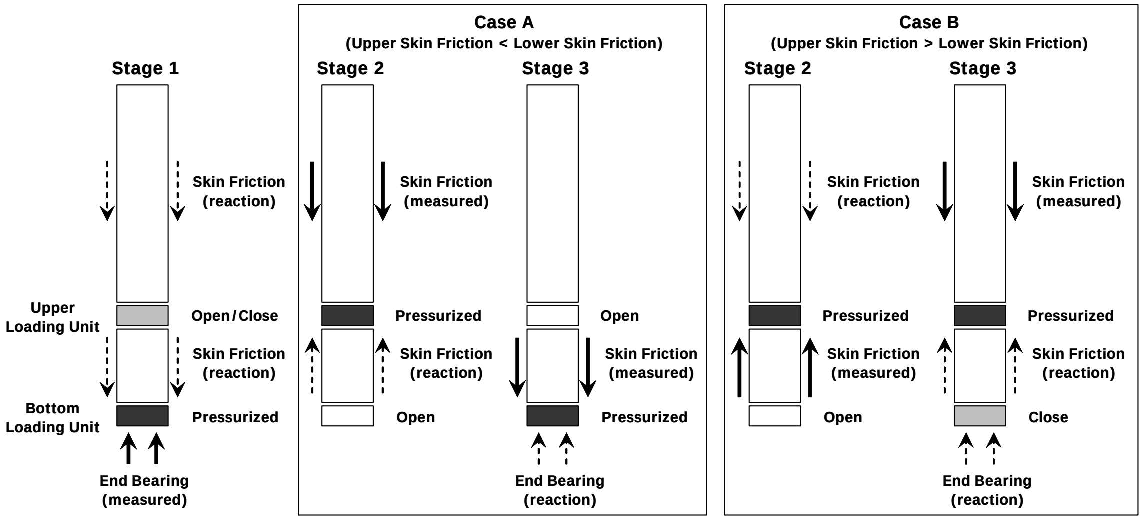


Figure 4 : Loading Sequence of Multi-level Bi-directional Test

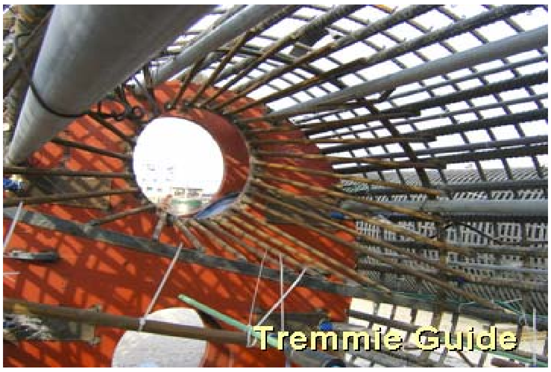
The objectives of the load test were evaluating ultimate skin friction and end bearing capacity of weathered rock and soft rock layers and end bearing capacity of medium rocks. In order to fulfill these objectives as much as possible, 4 test piles were utilized.

The location, length/depth of the shafts, location of loading unit, specification(capacity, maximum stroke, single/double acting), single or multi-level test were decided after considering estimated test pile capacity and test objectives, comprehensively. For TP 1 and 2, upper loading units were located at the boundary of weathered rock layer and soft rock layer so as to resolve clearly skin friction in each layer, and the socket length in soft rock layer were selected with the intention of evaluating ultimate skin friction. For TP 4, loading units were proportioned in order to ultimate skin friction and end bearing capacity of weathered rock, while considering the skin friction of weathered soil, alluvial and fill layers most effectively. TP 3, in which only 1 loading unit was installed at the bottom , was designed to find end bearing capacity of medium rock and skin friction of soft and weathered rock layers. Figure 3 shows the profile and location of the loading units. The shaft was drilled by the hammer grab down to casing driven weathered rock layer, then RCD was utilized. Casing for preventing hole collapses was kept within minimum length.

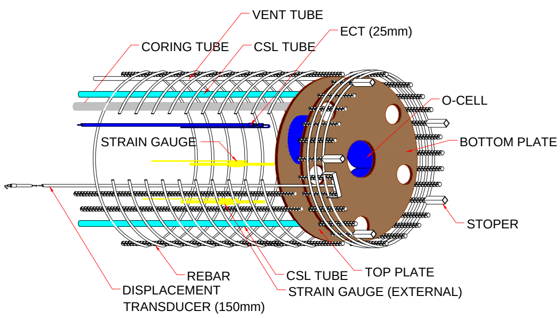
3. TESTS AND RESULTS

3.1 Offshore Area (Private-Investment Section)

The construction work for test piles (4ea) of large diameter pile in Incheon Bridge project was planned to commence on November 2004 simultaneously with the mobilization of marine equipments, loading and transportation, and to be completed on February 2005.
However, the pile load testing was completed at the middle of March 2005, 20 days behind the schedule, due to time loss caused by several reasons, such as working in the winter season, additional driving due to self-settlement of steel casing, unexpected change in weather condition during the test period, and transporting and setting of SEP barge on the test location. Therefore, total of five months were required for the construction of test piles (4 months) and performance of pile load test (1 month).
For concrete pouring of test piles, tremmie pipe was installed down to the pile tip by using tremmie-guide installed on upper bearing plate of O-cell. The concrete is filled up from the pile tip to the pile top through flow hole located on both sides (bottom/top) of bearing plate. This is to avoid any pore in concrete at O-cell area to exclude the grouting work for pile tip section. And, Coring-Guide Tube is installed down to the pile tip section in order to check the concrete condition of O-cell lower part through coring after completion of testing. (Refer to Figure 5.)
For O-cell applied to testing pile of Incheon Bridge project, Hydraulic pump and water were used to prevent any possible environmental pollution, not hydraulic fluid used for general loading equipment. And, separate vent tubes were installed to easily conduct the grouting for pore occurred by swelling of O-cell after testing. O-cell is arranged symmetrically to prevent eccentricity of pile with 2~5 numbers per test pile, which loads to the extent of approximately 4,800 ton in both(up/down) directions by using water pressure.

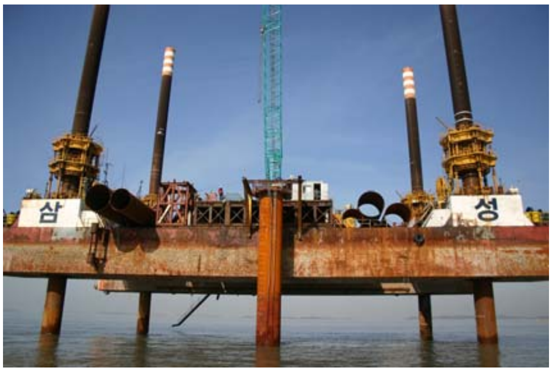


(a) Tremmie Guide



(b) Instruments

(c) Instruments on Pile Top

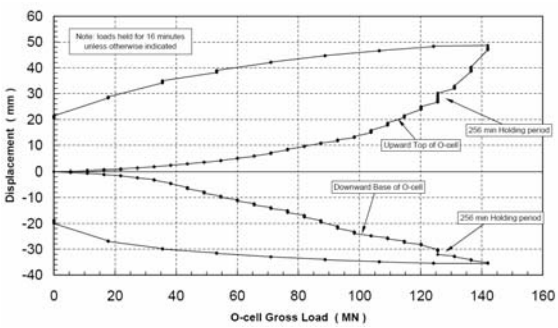


(d) Testing Pile

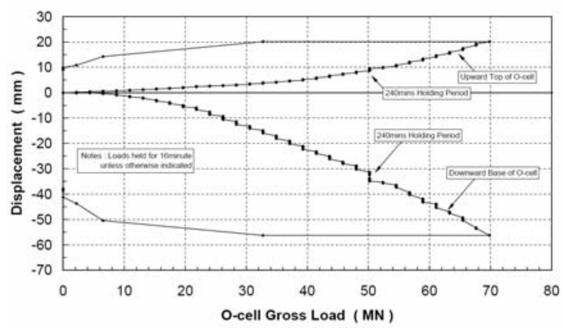
Figure 5: Instruments Details and Test Pile View

According to the schedule, test for 4 testing piles would be completed within total of 20 days, however, since more time were required due to SEP (self elevating platform) barge transporting and setting and unexpected severe weather conditions, total of 31 days were taken to com-

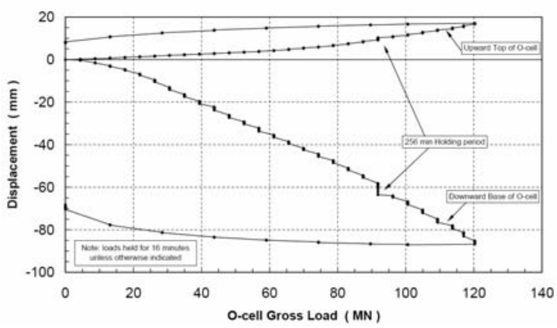
plete the test. In consideration of marine construction condition, the level of SEP barge was determined as reference level to measure the displacement. SEP barge was approached to the test pile as close as possible, and H-beam is fixed to install Reference Beam on both sides of test pile at the SEP barge side.
During the test, it was found through the data from O-cell Expansion Transducer (4ea) installed to measure displacement between bottom and top bearing plates that 50mm of bearing plate on bottom/top of O-cell slanted to the one side. The load is already exceeded the target load, but loading cannot be continued in the displacement smaller than maximum stroke (150mm).
O-cell is using high water pressure, thus in winter season, there is risk of freezing of pressure pump or hose. In order to prevent freezing, the water was mixed with anti-freezing solution, however, there was freezing phenomena in a water pump under high pressure, so any further loading could not executed any more.
At testing piles-TP-1(E5) and TP-4(E7), self-settlement of casing (driven to the extent of weathered rock 1m) was found due to partial decrease of strength on upper part of weathered rock, thus additional driving work was carried out. Thus, some loss occurred on section of measurement on the upper part of weathered rock.
The load achieved in the testing compared with the target load is as shown in Table 1, and the Load-Displacement Curves from test piles are shown on following Figure 6.



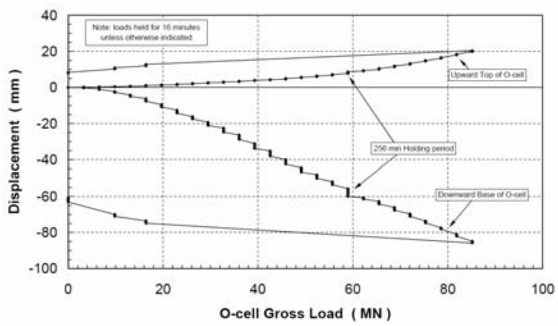
(a)TP-1(E5)



(b)TP-2(W6)



(c)TP-3(W8)



(d)TP-4(E7)

Figure 5. Load – Displacement Curve of Test Piles

3.2 Onshore Area (Government-Financed Section)

Tests for the Songdo Town area in the government-financed section were commenced in December 2005. 4 pilot drilled shafts were constructed and tested by bi-directional loading method. 3 of 4 piles have 2-layer cell system to investigate the skin friction at each ground stratum.

Figure 6 : Constructions and Tests of the Pilot Pile in the Onshore Area

Load-displacement curves of TP 1 are shown in Figure 7 in stages. At stage-1, lower loading unit was pressurized and the rate of displacement increase slowly after 6000 tonf. At stage 2, upper loading unit was pressurized while keeping the lower loading unit pressure valve open and the upper section reached ultimate state. At stage 3, lower loading unit was pressurized again with the upper unit open. Figure 6 shows the load-displacement curves in stage 1 and 3. In this combined curve, it is more evident that the slowdown of displacement at the stage 1 and that it is deviating from the overall trend. The reason can be attributed to malfunction of some of the loading jacks (total 14 in a layer) caused by tilting of the loading plate resulting in jamming of the cylinders. The tilting of the loading plate is somewhat unavoidable for large diameter piles. So it is recommended that reliable loading jacks be used which can accommodate some tilting of the loading plate. Table 3 summarizes the test results.

Table 3 : Load and displacement in each stage

Pile	Loading Stage	Nominal diameter (mm)	Max. load in one direction (tonf)	Displacement			Pressure (tonf/m^2)	Pressure (tonf/m^2)
				Upward	Pile head	Down-ward		
TP 1	Stage-1	2350	8,500	3.57	1.20	24.76	2,305	31,500
	Stage-2		10,750	103.55	98.70	22.51		
	Stage-3		10,000	27.15	0.31	48.35		
TP 2	Stage-1	1850	5,000	16.06	14.57	17.02	1,860	11,563
	Stage-2		1,563	88.92	83.22	2.5		
TP 3	Stage-1	1350	4,500	10.87	9.8	13.55	3,145	9,000
TP 4	Stage-1	1850	3,750	15.49	11.0	206.49	1,395	9,850
	Stage-2		2,350	112.71	111.96	32.13		
	Stage-3		2,466	48.80	0.11	30.84		

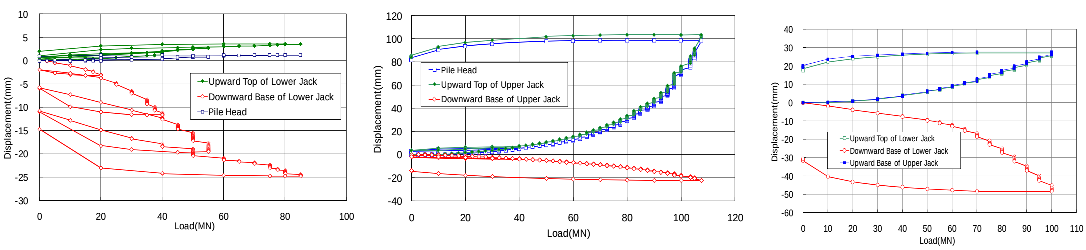


Figure 7 : Load-Displacement Curves of TP 1

In Figure 8, t-z and q-z curves are shown for all test piles. For t-z curves in soft rock layer show bi-linear trend, where after initial displacement of 2-4mm the slope decreases. Most curves shows strain-hardening trend. For weathered rock layer where casing was driven through, most curves are considered to reach ultimate state, whereas strain hardening trends are clear for weathered rock layer where RCD (reverse circulation drilling) method was used. This could be due to the effect of casing driving or the layer itself was weaker than underlying layer where casing was not needed to stabilize the hole. But the distinction of the two effects is not decided for now. The mobilized resistances at given displacements(5 mm, 10 mm, 23.5 mm are shown in figure 6. The data are still scattered, but generally the resistances get larger as the displacement are increased. This could be one of the reasons why so many empirical relations are proposed but still none of them gives satisfactory prediction for ultimate resistance for drilled shafts socketed into rocks.

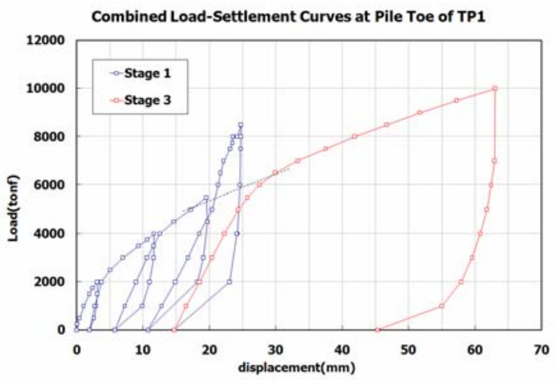


Figure 8 : Combined Load-Displacement Curves of Stage 1 and 3 of TP 1

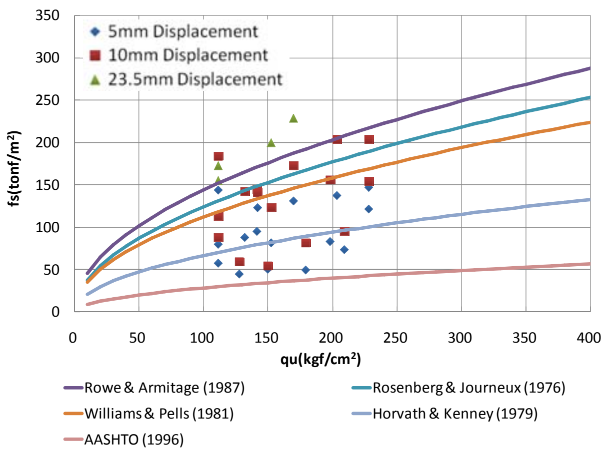


Figure 9 : Developed skin friction on mobilized displacements (Song et al, 2009)

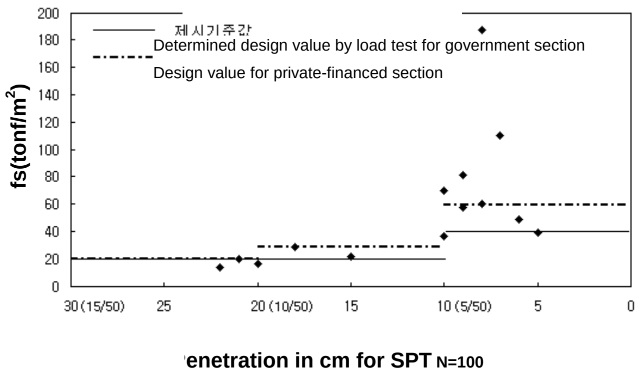


Figure 10 : Design skin friction in weathered rock determined by load test

As design values for skin friction in weathered rock layers, rather lowest measured values were adopted for design (Figure 10).

4. CONCLUSIONS

Osterberg Cell tests with massive load for 4 testing piles were successfully carried out at off-shore site for the sea-crossing section of the Incheon Bridge. 13799, 17369, 24531, 28958 ton of massive load were recorded. It is verified that large-volume loading test on full-scaled pile is possible to be conducted on the sea condition. In the event that the test was planned to be carried out as a preliminary load test, thorough preparations for O-cell test were required such as location of testing pile, O-cell capacity/location, measurement details, load capacity, sea condition, and etc. Only 15-20mm of displacement was shown under the maximum upward load except TP-1(E5). In view of the limit of stroke on O-cell, it is expected that more than 20mm of displacement would be monitored if O-cell was additionally laid considering the diameter of testing pile. In order to overcome the limit of the difference of bearing behavior in both directions, O-cell's Stroke shall become larger than current one(150mm). It is more desirable if water pressure system is improved to prevent freezing on severe test conditions.

For the verification of bearing capacity of drilled shafts at government-financed sections of Incheon Bridge, additional 4 pile load tests(1 by single level bi-directional test and 3 by multi-level bi-directional test) were carried out prior to the commencement of constructions under joint controls of all contractors. Piles socketed into weathered rocks and soft rocks were able to be tested up to record-breaking load of 31,500 tonf per pile, and design method could be verified for various conditions of all sections with relatively small number of test piles using multi-level bi-directional test. For soft rock layers, the skin friction generally increased even after the displacement of 15mm, and for weathered rock layers, the skin frictions of cased section was lower than uncased section. The bearing capacity design of participating sections were found to be on the conservative side and successfully verified.

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